IRREVERSIBILITY OF ELECTRICAL INSULATING MATERIAL PROPERTIES

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Summary Property changes in electrical insulating materials that appear during repeated voltage stress (e. g. in an applied voltage test) are an often discussed problem. The voltage exposure leads to irreversible changes in a negative sense as this investigation clearly demonstrates. A slow deterioration appears even in the case of the above mentioned applied voltage test when the irreversible effects of particular measurements superimpose. These are the effects of irreversible behavior of the insulating materials at applied voltage stress.

1. INTRODUCTION

The ensuring of reliability of electrical device operation increases with increasing requirements on its operation. If we imagine an electrical device as a chain of serial separated subsystems and elements, the insulating system will be one of its key components, influencing its whole reliability.

In engineering practice, there are some opinions ambiguously predicating about the irreversible changes that appear during the aging process of insulating system and cause its irreversible degradation. It has also been argued that the over-voltage test applied during electrical device operation has actually no influence on its final working lifetime. The low voltage level and short time of testing (existence of certain reversible area of electrical insulating materials) is reputedly the reason for this. Another opinion is that every over-voltage test reduces electrical device working lifetime (i.e. the absence of reversible area in electrical insulating materials). There are reversible changes of material structure during the voltage stress in the reversible area in time-voltage characteristics of insulating system, which doesn't lead to a decrease of the system lifetime.

This problem becomes very important especially in the case of devices working in extreme conditions (at the high temperatures), e.g. nuclear reactors, concretely the servomotors used for position control of fuel rods. Such devices must have an insulating system corresponding to the demands of a high temperature operation. These materials have different insulating properties and different aging mechanisms than common insulating systems. It isn't sufficiently known how the lifetime of these high temperature materials depends on voltage or thermal stress and mainly on eventual over-voltages and over-heating during their operation. The knowledge of electrical properties changes of these insulating materials is especially important for the construction and dimensioning of insulating systems as well as for planning of experiments dealing with these problems.

Figure 1 shows a waveform of breakdown voltage of dielectric material U_p in dependence on its lifetime during the over-voltage stress (curve A). The monitored parameter (e.g. insulating resistance, capacity, polarization index, tan δ) changes its actual values during the voltage aging of dielectric material, which means that time-voltage stress influences many of the monitored parameters.

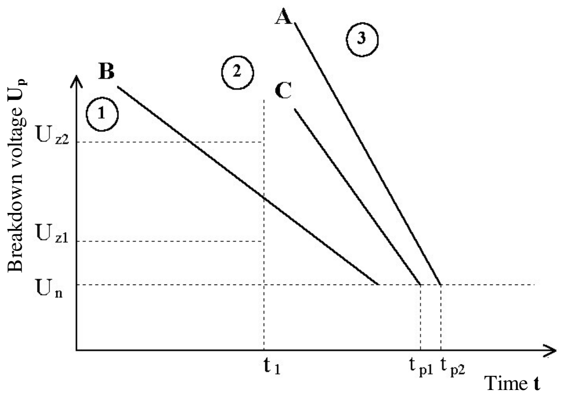

Fig. 1. Breakdown voltage U_p of dielectric during its lifetime at over-voltage stress

These values don't change a lot at the beginning of the aging, but when the aging process continues, degradation of dielectric material appears (curve B). Curve B presents the critical level. The overcoming of this limit causes irreversible changes in the material (a volume resistance and breakdown voltage dramatically reduce) and also lifetime is reduced (the material aging is then demonstrated by the curve C).

In Figure 1 U_n means the operating voltage, ① is the safe area (the area of reversible changes), ② is the faulty area (the area of irreversible changes) and ③ is the area of insulation breakdown. If we e.g. apply the voltage U_{z1} to the insulation in time t_1 (i.e. in the area of reversible changes), the original aging curve (curve A) will not change. However, if we applied the voltage U_{z2} to the insulating material (i.e. in the area of irreversible changes), we would irreversibly reduce the specific dielectric strength of the material, which would cause the reduction of its original lifetime (t_p) from t_{p2} to t_{p1} and the aging process would be demonstrated by the curve C. Just the determination of that start point (or time interval) of the irreversible process in the insulating material is very useful for practical application. In the case of flat curve B, short-term overloading of the insulating system by electric voltage can lead to a short circuit and to the end of the insulation lifetime. When curve B runs closely to curve A (i.e. it increases the area of reversible changes), the material is considered to be very resistant to the voltage overloading.

The aim of the investigation in this scientific field is to identify the existence of an irreversible area in the case of modern high-voltage dielectric materials.

The knowledge of waveform of the aging curve (curve A in the Figure 1) and the critical curve, which is the border between the area of reversible and irreversible changes (the curve B) contributes to the understanding of reversible and irreversible processes in modern high-temperature materials.

These materials are currently used for insulating systems in linear stepping motors for driving of control rods in nuclear reactors; in the aircraft industry etc. Obtained data will also enable the exact dimension of these high thermally stressed insulating materials.

Our department has dealt with these problems for a long time and partial results of our investigation have already been published [1-6]. The following text contains the complete collection of final results of the partial experiments obtained over several years.

2. EXPERIMENTAL

2.1 The description of tested material

This investigation is focused on trends of properties of materials used in unconventional operating conditions during the aging process, as mentioned above.

The material chosen for the purposes of this research is characterized by its considerable thermal resistance, approaching 500 °C. The tested material has been designed for work in extreme operating conditions under high temperature stress. The material composition – a noncalcinated mica (91 %) and a silicone binder (9 %) is based on the intended application. The silicone binder used in this material contributes to the thermal resistance of the composite. The binder consists of pure polymethylsiloxane and contains the highest proportion of a fully oxidized SiO_2 groups (82 %). This binder is also characterized by excellent binding forces to most of the inorganic materials, and by thermal resistance up to 300 °C without any marked deterioration of electrical or mechanical properties.

By compressing these components at high temperature and high pressure to the shape of compact hard boards, material was produced which conformed to the defined requirements – i.e. steady state thermal resistance up to 500 °C.

2.2 The aging process

The tested material was provided by a manufacturer in the form of hard boards 200x200 mm in size and with an average thickness of 0,315 mm. In this part of the experiment (i.e. before laboratory aging), all of the monitored material properties (see paragraph 2.3) were firstly measured. It was decided to apply heat and voltage stresses based on the typical usage of the material.

The thermal exposure was simulated only by unrepeated thermal stress of 320 °C for 500 hours on all samples in an aging oven. This technique was chosen, since it wasn't possible to apply both aging factors at the same time – which would have better simulated actual operating conditions. In this part of the experiment (i.e. after the thermal stress), all monitored material properties of the samples were measured again.

An accelerated electrical aging exposure then followed. For this purpose special brass electrodes 115x115 mm in size and with a thickness of 5 mm were made. The exposure times and electric field intensities were chosen to uniformly cover the whole spectrum of material operating stress. The selected values are presented in Table 1 below.

Tab. 1. Electric field intensities and exposure times

Exposure voltage (kV)	Electric field intensity ($kV.mm^{-1}$)	Time (hours)
3	9,6	80, 140, 200, 280
4	12,8	20, 50, 80
5	15,9	7, 14

The time limit of electrical aging was determined by the moment when the number of samples breakdowns started rapidly to increase; which means when the level of exposure voltage approached the level of breakdown voltage.

2.3 The compilation of applied tests

The selection of appropriate tests for this investigation was the essential part of the experiment. It had to be assumed that the tested material would have good properties including high thermal resistance [7-13] with regard to character of the material components – the mica and silicone binder.

The compilation of tests was then chosen on the basis of maximum predicative ability and information integrity of the tested material behavior. The final compilation of applied tests is presented in the Figure 2.

2.4 The evaluation of polarization and depolarization currents

The polarization and depolarization current analysis (PDC analysis [14]) is an appropriate method for evaluation of the behavior of electrical insulating materials, since these currents well describe the behavior of these materials during the application of dc voltage.

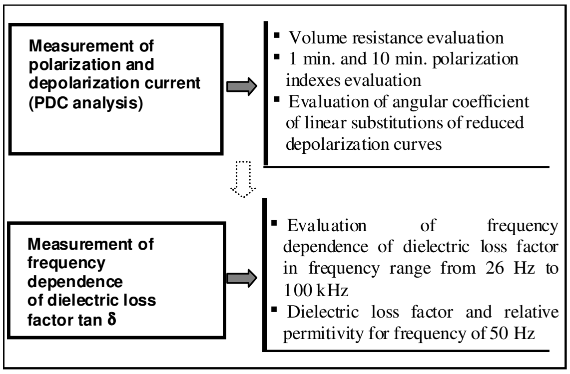

Fig. 2. Final compilation of applied tests

It is possible to estimate e.g. the values of volume resistance, volume resistivity and also polarization indexes from the measurements of polarization and depolarization current (i_p, i_d).

The polarization indexes are dimensionless variables, defined as a ratio between the polarization current at 15th and 60th second (minute polarization index p_{i1}) – in case of the polarization of single materials, eventually between 1st and 10th minute (ten-minute polarization index p_{i10}) for the whole winding or its parts.

The experiments realized in our department confirm that also the waveform of depolarization currents has sufficient sensitivity and gives full information about the behavior of electrical insulating materials.

It is also possible to obtain specific parameters of curves so called *Reduced Depolarization Curves* (RDC) [15] by the additional calculation from the depolarization current values. These reduced depolarization curves predict a lot about the properties of tested material.

The RDC method is based on a mathematical transformation of depolarization current waveform. Firstly, the i_d waveform is converted to so called *relative depolarization current* when the actual value of the current (dependant variable) is expressed by the relation between $i_{(t)}$ and i_{15} (i.e. depolarization current in 15th second), see equation (2). Then transformation of coordinates by the equations below follows:

$$x = \ln(t) - \ln(15) \tag{1}$$

$$y = ABS \ln\left(\frac{i_t}{i_{15}}\right) \tag{2}$$

where

x,y (-) are the transformed coordinates,
t (s) is the time,
i_t (A) is the instantaneous current at the time t,
i_{15} (A) is the depolarization current in 15th second.

The main parameter for the evaluation of insulating system properties is the angular coefficient of linear substitutions of reduced depolarization curves. The linear transformation of RDC is usually applied in the time interval from the 15th to 300th second in dependence on specific cases. In general, the higher value of angular coefficient means better insulation properties of the material. By contrast, a decreasing angular coefficient predicates a major content of polar impurities and thereby poor insulation properties.

One of the most important moments of the aging degree evaluation of tested material by the RDC method is the selection of a proper time interval for the transformation of a depolarization current. When we select a wider time interval, we get in to the area where the depolarization current shows only slow changes and a corresponding curve after this transformation has often nonlinearities on its end. This situation is presented in Figure 3.

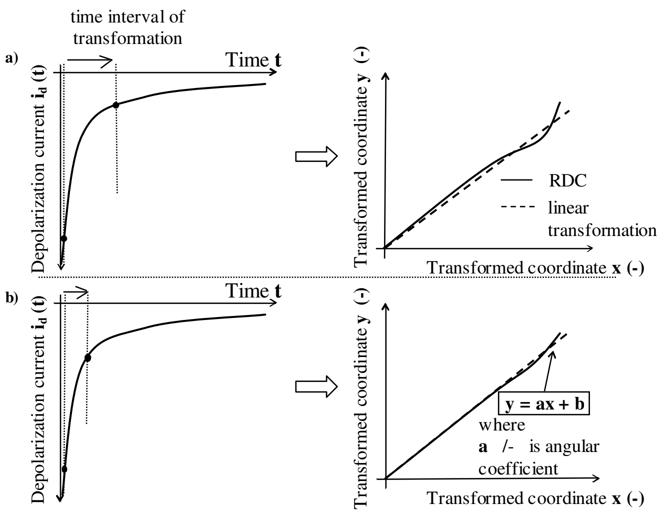

Fig. 3. Influence of the transformation interval on RDC final waveform and on corresponding linear substitutions; a) too wide time interval, b) optimal time interval

The occurrence of nonlinear areas in the end of RDC owing to the wrong selection of the time interval for transformation i_d is clearly shown in this figure. Too wide a time interval of transformation was chosen in the situation **a)**, which led to the occurrence of nonlinearities of RDC final waveform, accompanied by the poor accuracy of linear transformation (a poor correlation coefficient) compared to situation **b)**.

3. EXPERIMENTAL RESULTS AND DISCUSSION

All these problems have been the main aim of large-scale research with interesting results. Some of them are described in the following paragraphs.

It can be seen on the graphs that the first two points are shared with all curves. These correspond to the original condition DS (before laboratory aging) of the material and the primary thermal exposure of 320 °C for 500 hours. The following points then correspond to particular levels of voltage stress.

3.1 The partial results

Volume resistance, polarization indexes and RDC

Figure 4 illustrates the results of the volume resistance measurement. It is evident that the volume resistance markedly decreased in the case of high-stressed samples compared to the samples in the original condition.

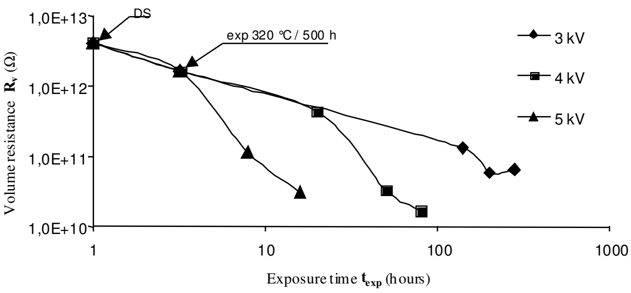

Fig. 4. Volume resistance vs. exposure time

Very interesting is the fact that the thermal exposure has only a slight influence on the volume resistance of material, which is obvious from the first two points of the curves. On the other hand the influence of voltage stress is much more apparent. The results of volume resistance measurements also demonstrate that the exposure by the higher voltage in a shorter time causes much higher degradation effects than exposure by the lower level of voltage over a longer time.

This expressive tendency was also confirmed by the results of the polarization and depolarization currents evaluation, which is shown in Figure 5. As is evident, the minute polarization index p_{i1} and also ten-minute polarization index p_{i10} decreased to the critical values near to 1 after the thermal and voltage exposure. The exposure of 3 kV that caused a markedly lower decrease of both indexes was observed.

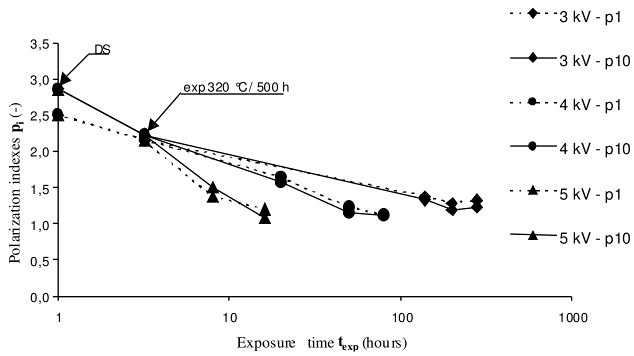

Fig. 5. Polarization indexes vs. exposure time

The other phenomenological methods also showed a significant ability to predict the influence of such exposure on the material properties (see Figure 6). Figure 6 shows the results of RDC method (angular coefficients of linear substitution after the transformation of RDC vs. exposure time).

It was found out that it is preferable to use the transformation of depolarization currents in the time interval from the 15^{th} to the 45^{th} second for the reason of major non-linearity of the reduced depolarization curves, in case of the wider time interval of transformation. After a decrease of angular coefficients of RDC (which refers to the degradation changes in the material) the increase of angular coefficients is observed, which probably predicts the disintegration of the material.

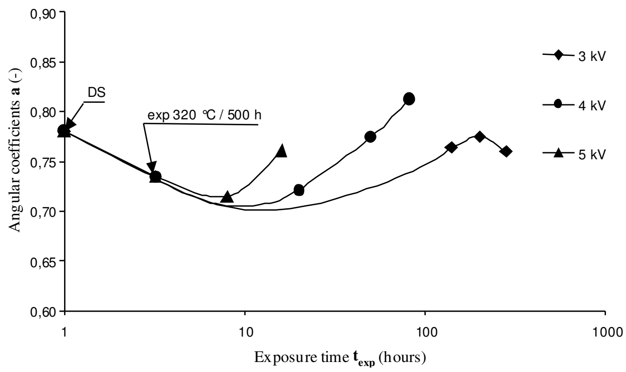

Fig. 6. Angular coefficients of linear substitution after the transformation of RDC vs. exposure time

Dielectric loss factor and relative permitivity

The frequency dependence of dielectric loss factor was measured in the frequency range from 26 Hz to 100 kHz (see Figure 7).

No extremes of frequency dependence of particular samples occurred in this frequency range. The measurement of tan δ and ε_r confirmed a better sensitivity to the changes of material properties at a lower measuring frequency.

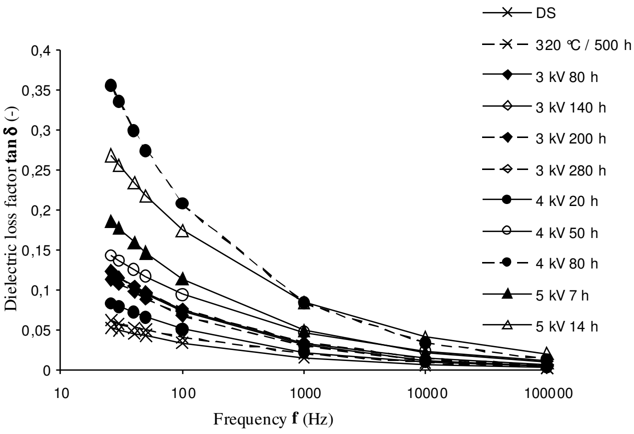

Fig. 7. Frequency dependence of dielectric loss factor for individual samples and exposures

The difference between both cut-off frequencies is up to 100 %.

The results of dielectric loss factor measurement for frequency of 50 Hz are shown in Figure 8.

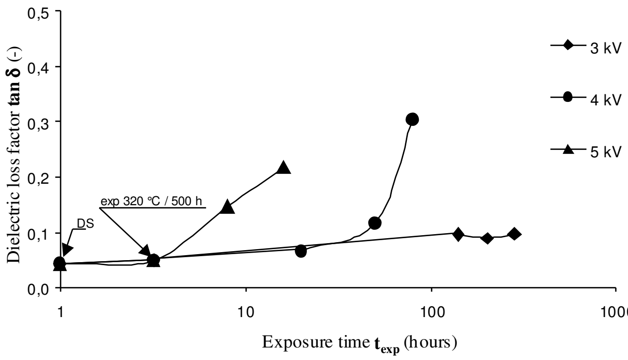

Fig. 8. Tan δ vs. exposure time

This measurement is very good at recognizing individual exposure degrees (these results clearly copy the intensity of the time-voltage stresses as is obvious from the curves for particular exposure rates). As we compare the waveforms, we can observe that the 3 kV exposure causes a slight increase of the dissipation factor. Another two exposures cause significant increase, so we can expect the irreversibility limit to be exceeded here.

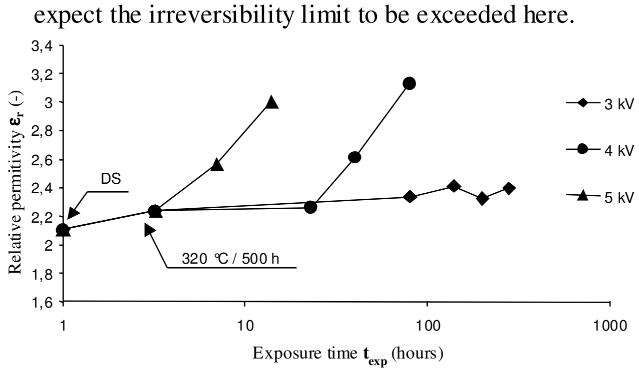

Fig. 9. Relative permitivity vs. exposure time

This phenomenon is documented very well in the 4 kV waveform, where just a slight increase of the dissipation factor is observed after the first two times (20 and 50 hours). The significant changes appear then during the exposure of 80 hours.

The results obtained from the relative permitivity measurement (which was similarly measured for the frequency of 50 Hz), also confirm the above-mentioned reaction of tested material on thermal-voltage stress (see Figure 9).

3.2 The main experimental results

The lifetime curve [16] from the partial results of the described experiment was subsequently calculated. This curve was created and approached by the help of the method of least squares and consequently related to the values of occurrence of the initial voltage of partial discharges (1,15 kV). Since the irreversible changes occurred right from the beginning of the voltage stress application, the limits were determined from the measured values. These limits are considered to be the continuation of the changes (but not initial changes) of monitored parameter during the aging process. An example is shown in Figure 10.

The determination of the limits for all the measured properties followed. The result is obvious from Figure 11.

The last figure (Figure 12) illustrates the final summary. Critical curve presents a summary of applied criterions of all measured properties during the voltage stress. The area determined by the lifetime curve and critical curve is the zone of intensive irreversible processes proceeding in the tested material.As results from the measured characteristics, the values of all monitored properties have changed during the voltage stress. We can also presume that it is not possible to document the existence of reversible area on the tested material in the range of the voltage stress which we chose and applied.

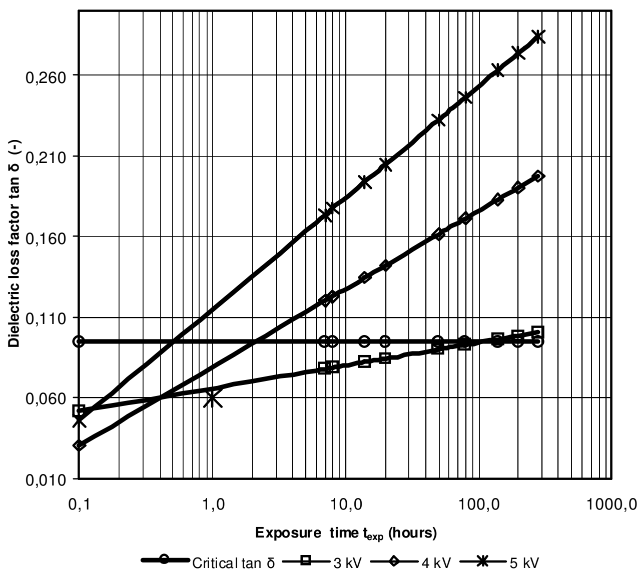

Fig. 10. Tan δ for particular levels of voltage stress with a time determination for chosen critical value

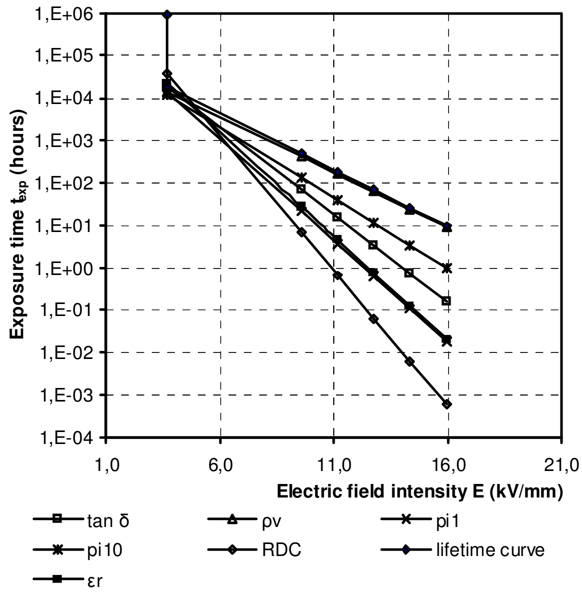

Fig. 11. Lifetime curve for particular measured magnitudes

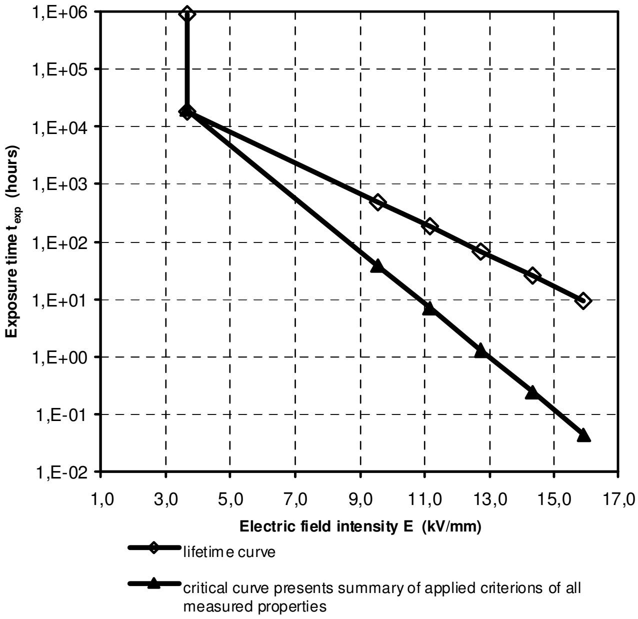

Fig. 12. Final lifetime curve

4. CONCLUSION

The results obtained contribute to the knowledge of the electrical insulating material structure and its changes under voltage overloading. The observed fact that a reversible area is almost nonexistent enables us to claim that the voltage stress exceeding the partial discharges initial voltage causes gradual degradation of the insulating material.

A data collection of property changes of tested material due to the voltage stress and also a verification of the fact that the reversible area of tested material properties is practically absent demonstrate the practical importance of the recorded results. The regular diagnostic measurements made on electrical devices are an example of practical application of obtained data. They are mostly terminated by the applied voltage test as a confirmative test for the further operation of these devices. The applied electrical voltage practically always exceeds the level of the initial voltage of partial discharges in this test. The periods of particular tests in the same voltage level are superimposed and the working lifetime of the insulating system is proportionally reduced owing to the existence of the irreversible properties of the insulating material (according to the results presented above).

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